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Relaying Selection with Network-coded Cooperative Protocols in Aeronautical Communications

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Abstract

In this article, we exploit the idea of network-coded cooperative protocol in aeronautical communications which combines different source nodes' information at the relay and joint decoding at the destination. Recently, the network coding in cooperative communications has been categorized into two mainstreams, bit-level and signal-level combinations, which are both discussed in the article. And to be exclusively, multiple access relay channel (MARC)is adopted. The mutual information expressions of both above-cited network-coded protocols are deduced, which prove that without proper selected relays to perform network coding, the spatial diversity of the proposed protocol cannot be obtained. This then leads to search for the selection and grouping algorithms. An adjacency matrix is defined to describe the connectivity of the nodes in one radio contact disk, so that, the selection and grouping of algorithm is equivalent to constructing this adjacency matrix to minimize the system outage probability evaluated in term of the mutual information. Besides, a network-coded cooperative protocol requires the acyclic network, of which the construction is to avoid loop-4 in the matrix. The article ends with simulations to demonstrate the viability of the proposed algorithms.

Keywords: communication; network coding; outage probability; mutual information; bit-level; signal-level

1. Introduction

Up to now, the air traffic control (ATC) and air traffic management (ATM) systems still work very well among the safest ways to travel and transport goods worldwide reliably. Aeronautical communications cover all the critical ATC/ATM communications, such as airlines communications (airline operation control (AOC) and aeronautical passenger communication (APC)), in support of both voice and data communications. However, the expected ongoing growth in air-traffic will lead to bottlenecks in air transportation in the near future if the existing ATC/ATM systems and paradigms do not hasten to make critical changes. This is especially true with aeronautical communications, the key enabler for an effective and safe air-traffic system. It is believed that the now saturated capacity of the infrastructures of existing ATC/ATM communications will be overloaded for the next ten years. For this reason, to expand the capacity, it is conceived to integrate satellites, aircraft, sensors and ground stations into the framework of future aeronautical communications to provide communication services anytime and anywhere.

A future air traffic control scheme is expected to contain hundreds or even thousands of airplanes. The resources of frequency and power are of great value for aeronautical communications and becoming challenges to the framework of future aeronautical communications. Moreover, the requirements for aeronautical communications including high mobility, high reliability and high data rate under constraints of complexity, size, and weight of avionics call for development of advanced algorithms and technologies[1].

Cooperative communications[2-7] have attracted considerable attention recently due to their enormous achievements in wireless networks. The concept of cooperative communications enables transmissions of information in network circumstances. The users not only send their own information but also share their resources (antenna, power and bandwidth) to help

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other users' transmissions over multiple paths in the network, forming a virtual multiple-input multiple-output (MIMO) system. Therefore, cooperative communications and networking are innovative paradigms to ensure significant reliability and capacity gains in aeronautical communications.

Interestingly, network coding[8] has naturally been associated with cooperative communications thanks to its salient feature of automatically employing intermediate nodes to combine code packets in cooperation. The network coding is originally considered extensively in the context of wired communications, but now strong interest emerges in applying it to wireless communications[9-14]. However, challenges also arise when we fit network coding into wireless situations characteristic of broadcasts, interference, fading and mobility. Thus, if network coding could win the same throughput gains as in the wired case, some measures must be taken to deal with synchronous compensation and channel equalization.

In network-coded cooperative communications, decode-and-amplify protocol and amplify-and-forward protocol are two basically employed coding protocols[2-4, 6]. They are both restricted by directional transmission between sources and relay. In decode-and-amplify, relay has to successfully decode the information received from the sources to provide effective diversity gains. In amplify-and-forward, relay also strengthens the noise level when amplifying the contaminated signals. However, since receivers are easy to know the local fading coefficients, they are able to adapt their transmission format according to the channel fading coefficients to minish the loss. Hence, appropriate relaying selection could offer diversity in either case[2].

Besides, in such a cooperative mode, nodes could act in a single transmission manner or in a cooperative transmission manner, specifically from the practical viewpoint, not all aircraft can be involved in every transmission due to their different status in mission, channel and motion. Each partner of an aircraft has a lifetime indicating its duration of presence in the radio contact circle region around the main aircraft. All these factors are possible to affect outage probability of the network. Therefore, grouping and partner selection may substantially reduce the consumption of communication resources and maintain a better quality of service (QoS) transmission link.

The main objective of this article is to illustrate some new forms of network coding which not only use the core idea to combine contents of information to obtain the significant throughput gains, but also avoid the difficult amendments for compensating the wireless fading effects. The solution in this article is focused on amplify-and-forward protocol and decode-and-forward protocol with network coding, which we propose by viewing the problem more generally in the overall dense network context. In particular, within the framework of future aeronautical communications, an algorithm is put forward to allocate nodes among multiple relays to aid the transmission nodes in considering the outage performances based on network-coded cooperative protocol and lifetime constraints. By proper selection of distributed relays, not only can the throughput gain of network coding be reaped, but also can a form of multi-user diversity be provided as well.

2. System Model

Now consider an aviation network with nodes which are roughly classified into sources (S_1 and S_2), relays (R) and destinations (D), where two or multiple sources send information with the help of available relay nodes in the middle of the network to the data processing center or a common destination. In practice, a relay may be an aircraft, a satellite or a sensor near the spot. The situation under study is modeled by a multiple access relay channel (MARC). It positions the sources symmetrically to the relay and destination. The geometric configuration made of S_1, S_2, R and D is a collinear setup with both sources at the origin and the destination a unit distance away from the origin. The relay moves along the line connecting the destination with the origin. Let the distance between S and R be d. Since radio terminals cannot transmit and receive simultaneously in the same frequency band, most cooperative strategies are based on half-duplex mode. The nodes are allocated orthogonal channels as time division multiple access (TDMA) reasonable to low cost requirements, and synchronization of TDMA is in packets level. S_1 and S_2 are assumed to send message with no priority. One block transmission is separate into two consecutive time slots t_1 and t_2, normalized to $t_1+t_2=1$. Furthermore, source codeword length for one block is N(for brief and to the point, the codeword lengths of S_1 and S_2 are equal and independent with each other), also split into two sub-blocks, each with t_1N, t_2N-long codewords accordingly(see Fig.1).

Here first comes the baseband-equivalent, discrete-time channel model.

$$y_j = h_{ij}x_i + z_{ij}$$

where x_i denotes an input signal from node i, y_i an output signal from node j. Assume that there are M nodes including sources, destinations, relays in the underlying network. Besides, we use lowercase for the signals and uppercase for the messages included in the signals, such as x_i and y_i represent signals, while X_i and Y_i messages in them. h_{ij} denotes a channel coefficient from node j to node i, such as from node S_1 to R, h_{s_1r}, reflecting the effects of path-loss and Rayleigh fading. It is evaluated by $h_{ij}=\sqrt{P_t}a_{ij}$, where P_t is the transmission power, $a_{ij}=\beta_{ij}/d_{ij}^2$ captures the path loss and Rayleigh-distributed fading with d_{ij} the distance between node i and node j, β_{ij} the Rayleigh-distributed fading factor, modeled by a complex Gaussian variable with variance σ_{ij}^2. $|\beta_{ij}|^2$ is an exponential distribution with the parameter $\lambda_{ij}=\sigma_{ij}^{-2}$. z_{ij}, which can also be modeled by a complex Gaussian variable with variance σ_0^2, represents an additive noise and other interference in the system.

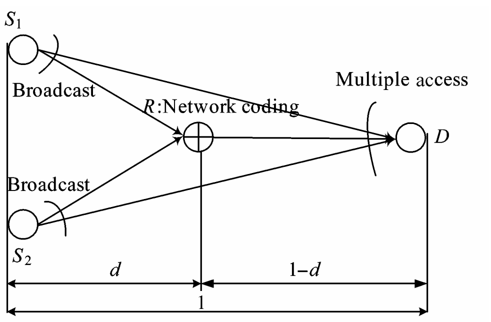

Fig.1 MARC model.

3. Network-coded Cooperative Protocol

The proposed cooperative protocol is based on network coding, which functions broadly across each layer in network protocol stack. This article illustrates two popular ways of combining information:the bit-level as a modulo-sum[9, 15] of information contents and the signal-level as mixed signals in the free space[11-12]. Fig.2 shows the two transmission stages.

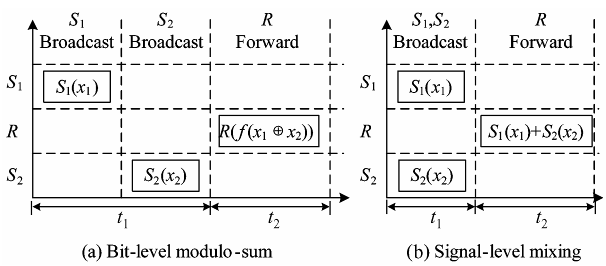

Fig.2 Network-coded cooperative protocols.

3.1. *Bit-level modulo-sum in relay*

In this mode, the protocol is rooted from decode-and-forward. Source nodes S_1 and S_2 are independent of each other and R is one of the relevant intermediate nodes. At R, two packets from S_1 and S_2 are separately decoded and combined with partial messages in an exclusive OR operation, as shown in Fig.2(a), then forwarded to D. Network coding procedure is accomplished in the sense of cooperation between the source nodes and the relay node. The detailed strategy is as follows.

(1) The first time slot t_1

Each source broadcasts codewords to R and D. S_1 and S_2 encode their own message $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ locally, by its own codeword book to $\boldsymbol{C}_{s_1}$ and $\boldsymbol{C}_{s_2}$, at the rate of

$$R_{s_1r}+R_{s_2r}=I(X_1,X_2;Y_r) \tag{1}$$

Then, S_1 and S_2 broadcast $\boldsymbol{C}_{s_1}$ and $\boldsymbol{C}_{s_2}$ to R and D. D receives and stores the data for decoding at the end of the block transmission. The baseband-equivalent discrete-time channel models at R and D are separately defined as

$$y_r=\begin{bmatrix} y_{r11} \\ y_{r12} \end{bmatrix}=\begin{bmatrix} h_{s_1r} & 0 \\ 0 & h_{s_2r} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} z_r \\ z_r \end{bmatrix} \tag{2}$$

$$y_{d1}=\begin{bmatrix} y_{d11} \\ y_{d12} \end{bmatrix}=\begin{bmatrix} h_{s_1d} & 0 \\ 0 & h_{s_2d} \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}+\begin{bmatrix} z_{d1} \\ z_{d1} \end{bmatrix} \tag{3}$$

In order to obtain the maximum throughput, sources broadcast at the rates defined by Eq. (1), and R is able to decode $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ with an arbitrarily low error probability. Of course, D would also receive the same messages in the first slot, but it cannot uniquely decode $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$. The reason lies in that from Fig.2, the physical channel from S to D is much more damaged than that from S to R; generally the following expression is tenable:

$$I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r)>I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)$$

(2) The second time slot t_2

D needs extra bits

$$t_1N(I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r)-I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_{d1}))$$

to decode the message successfully. Thus, the design is to let R send these extra bits to D at the rate of

$$R_{rd}=\frac{t_1N\left(I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r)-I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_{d1})\right)}{t_2N}=$$

$$\frac{t_1}{t_2}\left(I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r)-I(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_{d1})\right) \tag{4}$$

$$y_{d2}=h_{rd}x_3+z_{d2} \tag{5}$$

Specifically, the relay node, after decoding the codewords from S_1 and S_2, estimates $\boldsymbol{C}_{s_1}$ and $\boldsymbol{C}_{s_2}$, which then together coded by network codes to generate k_{net} check bits.

$$k_{net}=t_1N\left(I\left(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r\right)-I\left(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_{d1}\right)\right) \tag{6}$$

The above operation cooperatively performed by the source nodes and the relay node obeys the rule of coding with side information or binning procedure. Furthermore, binning is implemented by extra parity network coding bits (or syndromes). Relay's message, $\boldsymbol{X}_3$, the extra check bits generated based on sources' message, helps D to decode $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ (the elements of $\boldsymbol{X}_1$ and $\boldsymbol{X}_2$ belong to the set $\{1,2,\cdots,2^{t_1 N I(X_1,X_2;Y_r)}\}$) by restricting them to $2^{t_1 N I(X_1,X_2;Y_{d_1})}$ bins with the size of $2^{t_1 N(I(X_1,X_2;Y_r)-I(X_1,X_2;Y_{d_1}))}$ each. Moreover, the "binning" of R is a random set of bins' indexes to partition the sources' message space thus enlarging the distance of the codewords to make the sources' message decodable.

Consequently, the network-coded bits provide extra check bits for decoding in D. This is a design approach by joining channel coding in S_1 and S_2 with network coding in R, which proves very effective in suppressing noise and fading at the least cost of bandwidth. To some extent, the decode-and-forward protocol here can be regarded as a joint routing of parity check bits.

3.2. Signal-level mixing in relay

In the network-layer network coding protocol, multiple users each employ one time slot to transmit signals one after another to avoid interference, which is known as orthogonal transmission. Differently, in another popular physical layer network coding (PNC)[11-12], users send signals simultaneously(see Fig.2(b))without orthogonal scheduling, embracing interference in an innovative way. In the following, PNC is applied to MARC model and a detailed math model of the protocol is shown.

(1) The first time slot t_1

By the very broadcast nature of communication in the wireless channel, source nodes S_1 and S_2 send out signals simultaneously and both R and D receive mixed signals of S_1 and S_2 in free space. R receives a signal y_r, mixed with an additive noise z_r:

$$y_r = h_{s_1 r} x_1 + h_{s_2 r} x_2 + z_r \tag{7}$$

D also receives a signal y_{d1}, mixed with another noise z_{d1}:

$$y_{d1} = h_{s_1 d} x_1 + h_{s_2 d} x_2 + z_{d1} \tag{8}$$

Here y_r and y_{d1} are different from $\boldsymbol{y}_r$ and $\boldsymbol{y}_{d1}$ of Eqs.(2)-(3), because signal-level mixing way embraces two signals from S_1 and S_2 sent at the same time, and y_r and y_{d1} become one signal each after mixing in node R and D.

(2) The second time slot t_2

R retransmits and forwards the mixed signals received in the first time slot to the destination D. R amplifies the received signals, turning into y_r and then forwards y_r to D, which acquires another sample of the mixed signals of S_1 and S_2 to disentangle the signals. Then D receives a signal y_{d2} as follows:

$$\begin{aligned} y_{d2} &= h_{rd} y_r + z_{d2} = \\ & h_{rd} h_{s_1 r} x_1 + h_{rd} h_{s_2 r} x_2 + h_{rd} z_r + z_{d2} \end{aligned} \tag{9}$$

By arranging Eqs.(7)-(9), a matrix denoted by $\boldsymbol{A}$ is formed to express the relationship between the source signal matrix $\boldsymbol{X}$ at S_1 and S_2 and the output signal matrix $\boldsymbol{Y}$ at D. Accordingly, the equation $\boldsymbol{Y}=\boldsymbol{AX}+\boldsymbol{Z}$ can be easily acquired, i.e.,

$$\begin{bmatrix} y_{d1} \\ y_{d2} \end{bmatrix} = \begin{bmatrix} h_{s_1 d} & h_{s_2 d} \\ h_{rd} h_{s_1 r} & h_{rd} h_{s_2 r} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} z_{d1} \\ z_{d2} + a_{rd} z_r \end{bmatrix} \tag{10}$$

Decoding of PNC is to disentangle the mixed signal $\boldsymbol{Y}$ by searching for the maximum independent components with an improved joint approximate diagonalization of eigen-matrix (JADE) algorithm[15] on the assumption that signals are independent of each other. Generally, this holds true in most cases, for each encoder has independent code books. Hence, PNC protocol can reduce time slots from 4 to 2. Apparently, it increases network capacity and enhances bandwidth utilization ratio. Besides, by making use of the blind signal separation method, the requirements for senders' synchronization and channel state information can be removed, which is very attractive, for synchronization is always bothering and tedious in wireless communications.

However, both network-coded protocols still have to perform careful selection of relays due to the diversity demanded by wireless transmissions. Then, after limited calculation based on the obtained local channel state information, the measurement of a relay node could be achieved, according to which a proper one could be chosen.

4. Mutual Information

It is difficult to extend network coding to the fading environment, which is the key motivation for the selection of relays. By carefully designing the selection criteria and algorithm, we could obtain a network-coded cooperative protocol with spatial diversity. Thus, this section is meant to discuss the strategy of relaying selection. The performance of the above-mentioned protocols could be defined in terms of outage probabilities symbolizing the robustness of a communication system. The outage behavior is given that an outage event happens when a system fails to support an instantaneous information rate of R_t[2]. The probability of an outage event occurring is defined as outage probability, Prob (I<R_t), where I is the mutual information. And outage probability can be obtained from the cumulative distribution function (CDF) of the mutual information. Therefore, this article deduces the mutual information and attains the CDF of mutual information through Monte Carlo simulations. In the proposed cooperative protocol, each symbol occupies 2 orthogonal channels as shown in Fig.2. For each source node, the mutual information should be divided by a factor 2.

4. 1. Bit-level protocol mutual information

In order to ensure the system throughput, it is necessary to quote the conclusion in Section 3 that the transmission rate must satisfy the requirement for the relay to decode the information successfully. Hence, in the first time slot, the mutual information between input $\boldsymbol{X}_1$, $\boldsymbol{X}_2$ and $\boldsymbol{Y}_r$ at the relay is

$$I_{BNC}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_r)= \frac{1}{4}\log_2[1+\gamma(\left|a_{s_1r}\right|^2+\left|a_{s_2r}\right|^2)+ 2\gamma^2\left|a_{s_1r}\right|^2\left|a_{s_2r}\right|^2] \tag{11}$$

where $\gamma=E_S/\sigma_0^2=P_t/(W\sigma_0^2)$ is the input signal to noise ratio(SNR), W is the bandwidth. According to min-cut max-flow theorem, we get

$$I_{BNC}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)=\min\{C_{sr},C_{sd}+C_{rd}\}$$

where C_{ij} represents the capacity of the channel from node i to node j. If relaying were successful, without considering the new information in the second time slot from source nodes, the capacity could be assumed:

$$I_{BNC}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)=C_{sr}$$

Then, Eq.(11) is also the maximum of the mutual information between sources and destination, thus

$$I_{BNC}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)=\frac{1}{4}\log_2[1+\gamma(\left|a_{s_1r}\right|^2+ \left|a_{s_2r}\right|^2)+2\gamma^2\left|a_{s_1r}\right|^2\left|a_{s_2r}\right|^2] \tag{12}$$

Taking into account the protocol described in Section 3, the users' broadcast information is at the rate of Eq. (1). Thus, the underlying principle is to make sure that R can successfully decode the information received. From Ref. [2], the conclusion of decode-and-forward protocol indicates that fixed decode-and-forward does not offer diversity gains for large SNR because R is required to fully decode the source information. Besides, to make sure that Eq.(12) is achieved, relaying selection is responsible for the diversity demanded. Therefore, in order to make sure of enough good channel status from source to relay, the selected relay should fundamentally satisfy

$$|a_{s_1r}|^2\geq\left(2^{2R_t}-1\right)/\gamma\cap|a_{s_2r}|^2\geq \left(2^{2R_t}-1\right)/\gamma \tag{13}$$

4. 2. Signal-level protocol mutual information

The mutual information of PNC able to achieve can be written as

$$I_{\rm PNC}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)=\frac{1}{2}\log_2\left(\left|\boldsymbol{I}+\boldsymbol{A}^H\boldsymbol{Z}^{-1}\boldsymbol{A}\right|\right)= \frac{1}{2}\log_2[1+\gamma(\left|a_{s_1d}\right|^2+\left|a_{s_2d}\right|^2)+ \gamma\frac{|a_{rd}|^2}{(1+|a_{rd}|^2)}(\left|a_{s_1r}\right|^2+\left|a_{s_2r}\right|^2)+ \gamma^2\frac{|a_{rd}|^2}{(1+|a_{rd}|^2)}(\left|a_{s_1d}\right|^2\left|a_{s_2r}\right|^2+\left|a_{s2d}\right|^2\bullet \left|a_{s1r}\right|^2-2\,\mathrm{Re}\{a_{s1r}^*a_{s2r}a_{s1d}a_{s2d}^*\})] \tag{14}$$

where $\mathbf{Z}=\begin{bmatrix}\sigma^2 & 0\\ 0 & \sigma^2(1+a_{rd}^2)\end{bmatrix}$ the covariance matrix of the noise.

PNC is based on amplify-and-forward protocol. As it is hoped this protocol could provide spatial diversity besides throughput improvement, a straightforward approach is to compare it with directional transmission, in which, $\boldsymbol{A}=\begin{bmatrix}h_{s_1d} & 0\\ 0 & h_{s_2d}\end{bmatrix}$. Therefore,

$$I_{DT}(\boldsymbol{X}_1,\boldsymbol{X}_2;\boldsymbol{Y}_d)=\frac{1}{2}\log_2[1+\gamma(\left|a_{s_1d}\right|^2+ \left|a_{s_2d}\right|^2)+2\gamma^2\left|a_{s_1d}\right|^2\left|a_{s_2d}\right|^2] \tag{15}$$

In order to render the performances of PNC better than those of directional transmission, Eq. (15) could be compared with Eq.(14) and the relay should be selected by the following rule:

$$\frac{|a_{rd}|^2}{1+|a_{rd}|^2}(\left|a_{s_1d}\right|^2\left|a_{s_2r}\right|^2+ \left|a_{s_2d}\right|^2\left|a_{s_2r}\right|^2)>2\left(\left|a_{s_1d}\right|^2\left|a_{s_2d}\right|^2\right)$$

After rearranging, it becomes

$$(\left|a_{s_2r}\right|^2>\frac{1+|a_{rd}|^2}{|a_{rd}|^2}\left|a_{s_2d}\right|^2)\cap (\left|a_{s_1r}\right|^2>\frac{1+|a_{rd}|^2}{|a_{rd}|^2}\left|a_{s_1d}\right|^2) \tag{16}$$

5. Relaying Selection Algorithm

In aeronautical communications, all nodes are featured by high mobility. The outage events happen when cooperative nodes fail to decode source messages or two independent messages are mistakenly decoded at the destination. A single relay node alone is not the optimal solution, since it sometimes leads to nothing but increased complexity of the system. As a result, more than one node is required to effectuate transmissions.

Among all the relay nodes to be selected, each relay's mutual information could be calculated according to Eq. (12) or Eq. (14)depending on which network-coded protocol is chosen and then arranged in a numerically descending order as follows:

$$\left.\begin{aligned} I_{BNC}(n_r) > I_{BNC}(n_r-1) > ... > I_{BNC}(1) \\ I_{PNC}(n_r) > I_{PNC}(n_r-1) > ... > I_{PNC}(1) \end{aligned}\right\} \tag{17}$$

where n_{re} is the number of relay nodes.

Of course, the relay node with the largest mutual information has the precedence of being chosen. However, the selection and grouping algorithm must fit in with the dynamic topology of the aeronautical networks characteristic of high mobility. Nodes in one radio contact disk have a temporary topology and every node has to maintain a list describing the connectivity to the other nodes in the disk. The updating period of the list is dependent on the lifetime of a node as a relay, which is called a lifetime period, $\min(T_{life}(v_1), T_{life}(v_2), …,T_{life}(v_n))$, where $v_i(i=1, 2, …, n)$ represents the node in the concerned network. So an adjacency binary matrix is proposed to show the connectivity links (see Fig.3). The construction of adjacency binary matrix is described as below.

We use an adjacency binary matrix to describe the real-time topology of the network. Specifically, based on the number of nodes M in a radio contact and two cooperation orthogonal channels, the adjacency matrix (see Fig.3) is divided into two square binary matrixes, $\boldsymbol{P}$ and $\boldsymbol{L}$, and constructed with M rows and $2M$ columns.

$\boldsymbol{P}$ is a square binary matrix, where p_{ij} describes the connectivity link among the senders in the first channel. p_{ij} =1 represents the event, i.e., the node j sends its own information to node i. Diagonal elements are set to p_{ij} =1 since a node knows its own information. Otherwise, p_{ij} =0. $\boldsymbol{L}$ is a lower triangle binary matrix, where l_{ij} describes the connectivity link in the second channel. l_{ij} =1 represents the event, i.e., node j sends relay information to node i. When i<j, then l_{ij} =0 because node j must relay its information to node i before node i implements network coding. The binary matrix, which describes the instantaneous network topology, maintains stable at least for a block transmission.

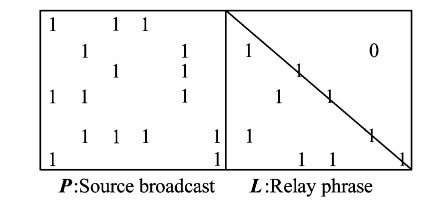

Fig.3 Adjacency binary matrix.

Two primary terms need to be presented firstly, column weight and row weight. The adjacency matrix is a binary matrix with entries either being "0" or "1", and it is also a sparse matrix. So, column weight is the number of "1" entries in each column. Likewise, row weight is the number of "1" entries in each row. Literally, column weight means the number of cooperation nodes to the specific node, while row weight means the number of source nodes participating in the network coding procedure.

Let $\lambda_j(1\le j\le M)$ be the weight of columns in $\boldsymbol{P}$, and $\rho_i(1\le i\le M)$ the weight of rows in $\boldsymbol{P}$ while the partner number allocated to a node would be λ_j-1 and the number of source nodes participating in the network coding procedure in a relay node would be ρ_i-1.

$\boldsymbol{P}$ describes not only the connectivity among the nodes in a radio contact but also the relationships of the cooperation.

The way to construct an adjacency matrix to minimize the aeronautical network outage probability and link bit error probability in a lifetime is the key issue of the selection and grouping algorithm. The outage probability contingent on the network channel state information is evaluated for every node in the disk. To reduce the complexity, the local optimization is adopted in the following detailed description of the algorithm.

The destination node will perform joint decoding of received information from S_1, S_2 and R. If with loop network existing, the joint decoding performance will be dramatically degraded, for lack of extinct information required in the iterative decoding procedure[8]. Therefore, the adjacency matrix should avoid short loops[16] to guarantee the network to be an approximately acyclic one. Short loops mainly contain 4 or 6 loops. According to performance analysis, containing loops of length 4 is the most unexpected.

Let $G=(V,E)$be a communication network, where V is the set of source nodes, relay nodes and destinations $|V|=M$ and E is the set of links between the nodes. If there exists a link sequence: (v_0,v_1), (v_1, v_2), $(v_2, v_3)$and(v_3, v_0), there is a loop of length 4 in the network. We refer to such loops as loop-4 expressed by Fig.4, and in general a loop of length n_l is a loop-n_l. There is at most one edge between any two nodes, and so the shortest length a loop can have is 4.

$$
\boldsymbol{P}=\begin{bmatrix}
1&0&1&0&1&0&0&0&1\\
0&1&1&0&1&1&1&0&0\\
0&0&0&1&0&1&0&0&0\\
0&0&0&1&1&0&1&1&0\\
0&1&1&1&0&1&0&0&1\\
1&1&0&0&0&0&1&1&0
\end{bmatrix}
$$

0

1

Fig.4 Loop-4 detection and removal.

Loop detection and removal are first to detect loops, and then exchange certain edges within the graph to eliminate these loops without simultaneous creation of new loops. Repeat this operation until there are no such loops left behind.

Here, an algorithm based on adjacency matrix $\boldsymbol{P}$ is used. After $\boldsymbol{P}$ has been generated, $\boldsymbol{L}$ could be constructed by the working mode of nodes and in the cooperative mode, the element is set to be 1, otherwise 0.

As a result, in the partner selection and grouping algorithm, firstly it is required to construct randomly $\boldsymbol{P}$ to allocate cooperation nodes at will and then locate loop-4 to be removed, thus forming an approximately acyclic network as a basis to evaluate the outage probabilities and average them over all the nodes in the network. Finally necessary steps should be taken to minimize the averaged outage probability.

The algorithm can be described as follows:

Step 1 Randomly construct the adjacency matrix with constant column weight and row weight.

Step 2 Detect loop-4 in the adjacency matrix and remove the detected loops by using the method of exchanging edges[16]. As shown in Fig.4, loop-4 is detected and removed by no more new loops introduced.

Step 3 Compute local mutual information of the relay node over all the nodes on the basis of available channel knowledge and the current topology to obtain Eq.(17) arranged in a numerically descending order. Moreover, the relay must satisfy the rule given by Eq.(13) or Eq.(16) in Section 4.

Step 4 Assuming the node i has partners, find a node j among all the other partners(nodes in one radio contact disk), whose partners exchanging with i's partners would result in better outage performances, then exchange elements in the matrix as illustrated in Fig.5.

Step 5 Repeat Steps 2-5 for all the nodes in this radio contact disk until no exchange is required any more.

$$
\begin{array}{c}
\text{Nodes}\\
\begin{array}{c}\text{Partners}\\ i\text{'s}\\ \\ j\text{'s}\\ \\ \\ \end{array}
\begin{array}{c}
\begin{array}{ccccccccc}&&&&&&i&j&\end{array}\\
\begin{bmatrix}
1&0&1&0&1&0&0&0&1\\
0&1&1&0&1&1&1&0&0\\
0&0&0&1&0&1&0&0&0\\
0&0&0&1&1&0&0&1&0\\
0&1&1&1&0&1&0&0&1\\
1&1&0&0&0&0&1&1&1
\end{bmatrix}
\end{array}
\end{array}
\longrightarrow
\begin{array}{c}
\text{Nodes}\\
\begin{array}{c}
\begin{array}{ccccccccc}&&&&&&i&j&\end{array}\\
\begin{bmatrix}
1&0&1&0&1&0&0&0&1\\
0&1&1&0&1&1&0&1&0\\
0&0&0&1&0&1&0&0&0\\
0&0&0&1&1&0&1&0&0\\
0&1&1&1&0&1&0&0&1\\
1&1&0&0&0&0&1&1&1
\end{bmatrix}
\end{array}
\begin{array}{c}\text{Partners}\\ j\text{'s}\\ \\ i\text{'s}\\ \\ \\ \end{array}
\end{array}
$$

Fig.5 Exchanging partners in adjacency matrix.

6. Simulations and Results

A simulation based on network-coded cooperative strategy is fulfilled by means of the above-described selection algorithm to demonstrate its performances. For simplicity, the two stages of first and second channels are set to be equal 1/2. It should be pointed out that the simulation results are numerically evaluated in terms of a non-closed form of expression, so they only reflect qualitatively system's behavior and characteristics.

According to the prediction made by Civil Aviation Administration of China, in the future, there will be 4000 aircraft in the field of China civil aviation. Therefore, it stands to reason that one radio contact disk contains 100 communication nodes. In practice, it is likely to be a high density terminal region. Different cooperative node numbers are chosen to perform the simulation by taking into account the complexity of receivers.

Fig.6 shows the relationship between the outage probability and R_t(bit/(s·ch)), where "ch" represents each channel use. It is commonly perceived that outage probability ascends with R_t increasing. The outage probability performance of directional transmission is also shown as the reference. It can be understood that the signal-level has the best outage probability performance in the three sorts of transmissions. Compared to the directional transmission, there is a 1.3 bit/(s·ch)rate improvement for the signal-level network-coded strategy and a 0.8 bit/(s·ch)rate improvement for the bit-level network-coded strategy. The results also prove that the physical layer network coding has more throughput gains than the bit-level network coding.

Firstly Eq. (13) and Eq. (16) are used as directives for relaying selection and comparison is made between the results obtained with and without relaying selection (see Fig.7). In the figure, the four curves can be categorized into two kinds: the bit-level and the signal-level. Obviously, the signal-level has much better outage probability performances. With relay selection, the bit-level network coding wins at most about 0.5 bit/(s·ch) rate improvement while the signal-level network coding about 0.3 bit/(s·ch) rate. This means that the performances of the signal-level is less dependent on the relaying selection because in amplify-and-forward protocol relay does not need complete decoding of information. In contrast, the bit-level strategy is much more closely linked to the relaying selection.

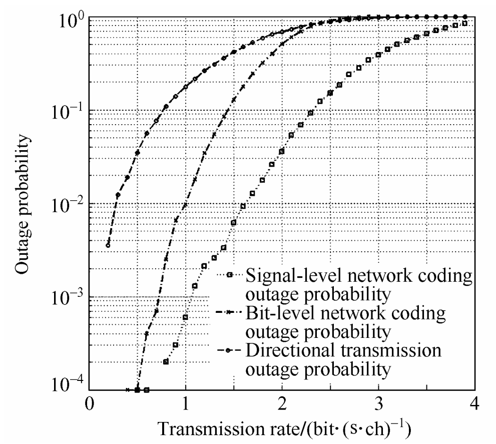

Fig.6 Transmission rate vs outage probability, SNR=3 dB.

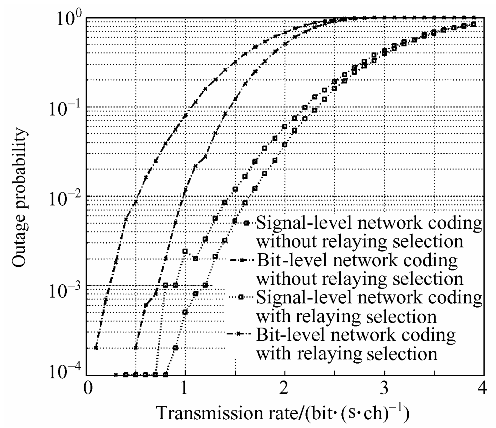

Fig.7 Comparison of outage probability performances abtained with and without relaying selection.

Fig.8 compares the capacity of the bit-level to that of the signal-level network coding. Clearly, the signal-level network-coded strategy gains much more improvements in capacity than the bit-level because the former embraces the interference and makes full use of the available channels.

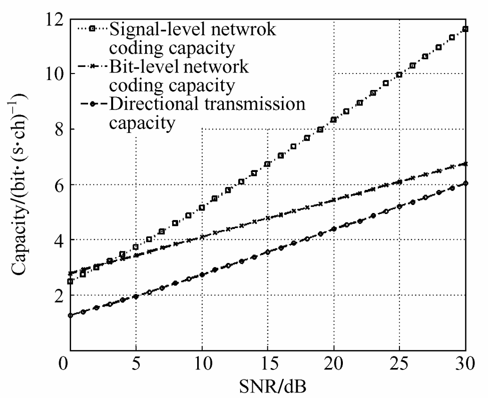

Fig.8 Capacity vs SNR.

Finally, multiple relaying selections with the number of cooperative nodes n_{re}=3, 5, 7 are made and the results are displayed in Figs. 9-10 respectively. The simulation effectively computes the average outage probabilities of all users for a given network with the

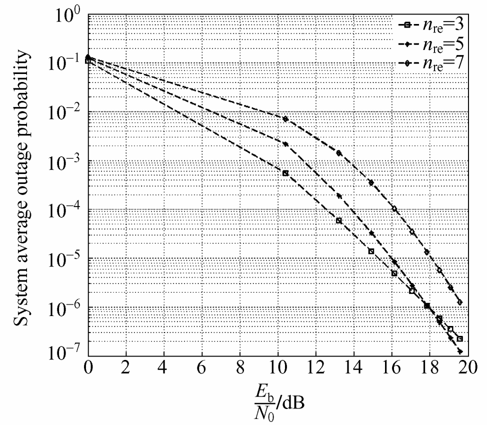

Fig.9 System average outage probability performnces, R_t = 0.35 bit/(s·ch).

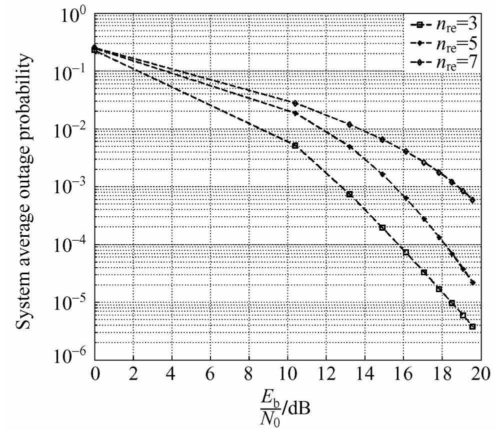

Fig.10 System average outage probability performances, R_t= 0.50 bit/(s·ch).

same SNR defined as the ratio of energy per bit and single-side noise power, E_b/N_0 to all the mobile nodes in the disk. From the figures, it can be concluded that the gains rise with the increase in the number of cooperative nodes, n_{re}. However, at high SNR, the increase in gains becomes much less obvious, sometimes only leads to the increase in the complexity of system.

7. Conclusions

Cooperative communications for aeronautical application presents itself a potentially fruitful technique that would result in remarkable gains both in capacity and reliability. Furthermore, two mainstream of network-coded schemes, bit-level and signal-level network coding, are employed for cooperative aeronautical communications, and simulations the article conducted demonstrate the potential improvements are achievable in the throughput of the system. With the two network-coded strategies, the presented selection algorithm has laid focus on the joint decoding efficiency and outage probability performance analysis. Besides, the spatial diversity for multiple relaying is also considered to overcome the high-speed movement of an aircraft. To sum up, the network coding performs outstanding cooperation in large-scale wireless networks with the help of proper relaying selection. The proposed cooperative relaying selection algorithm balances the required reliability and the throughput of the whole network.

However, since aeronautical communications are demanded to be much stricter than any common communications in terms of security and safety, the signal-level network-coded strategy is still far from the practice, which requires consideration in implementation problems. The selection algorithm used for the problem is run on a local optimization method by exchanging cooperative nodes already allocated to the nodes in the initial process. Consequently, in the future research, much more attention should be paid to the global optimization algorithm, and the incompatible requirements for complexity and performances must be carefully traded off due to the limited size of airborne avionics.

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